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SYSTEMS FOR SPACE APPLICATION  
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NASA Grant NAG 5-1319: Solid State Laser Systems for  
Space Application

Annual Report through January 1994

Richard B. Kay, Principal Investigator

### Introduction

Since the last report several things have happened to effect the research effort. In laser metrology, measurements using Michelson type interferometers with an FM modulated diode laser source as described by Kikuta et al.<sup>1</sup> and Seta and Ward<sup>2</sup> have been performed. The discrete Fourier transform technique described by Suematsu and Takeda<sup>3</sup> has been implemented. Problems associated with this technique as well as the overall FM scheme have been identified, in least in part. The accuracy of the technique is not at the level we would expect at this point. We are now investigating the effect of various types of noise on the accuracy as well as making changes to the system. One problem can be addressed by modifying the original optical layout.

Our research effort was also expanded to include the assembly and testing of a diode pumped Nd:YAG laser pumped Ti sapphire laser for possible use in sounding rocket applications. At this stage, the diode pumped Nd:YAG laser has been assembled and made operational. Finally, the grant period was extended at no cost to NASA to last until August 1994, at which time a final report will be submitted. Discussion of the above summarized research elements now follows.

### Metrology Research

This research is based on an interferometric scheme where by absolute distances are determined as a result of a (linear) frequency modulation of the source laser. Recall that in the

semi-annual report it was shown that the difference in length  $L$  of two arms of a measuring Michelson interferometer could be determined in terms of the difference in length  $L_R$  of two legs of another (reference) interferometer by:

$$L = [\omega_S(t)/\omega_R(t)] \cdot L_R \quad 1]$$

where

$$\omega_i(t) = d\phi_i/dt = 2\pi f_i + \dot{\theta}_i(t) = 2\pi L_i/\lambda \cdot \left[ \alpha_o + d\{\Delta\alpha(t)t\}/dt \right]. \quad 2]$$

In Eq. 2,  $f_i = 2\pi\alpha_o L_i/\lambda$  would be the beat frequency due to the path difference in an interferometer's legs if there were no non-linearities in the frequency scan of the laser and  $\dot{\theta}_i(t) = 2\pi L_i/\lambda \cdot \{d\Delta\alpha(t)t\}/dt$  accounts for non-linearities which are assumed small.<sup>3,4</sup> Thus  $\omega_S$  and  $\omega_R$  are the beat frequencies at the detector due to the difference in path traveled in the measurement (s) and reference (R) interferometers as the source laser is scanned in frequency. These quantities are retrieved from the intensity at the detector as a function of time which was digitally recorded as the base data. These data are then a superposition of two frequency spectrums which include nonlinearities due to non linearities in the optical frequency scan.

The ratioing scheme indicated by Eq.1 portends to get rid of these nonlinearities which are expected to be present in both the measuring and reference frequency data. A fast fourier transform technique separated these data in frequency space and Hanning windows were used to isolate each region. The data for each frequency region was the "phase unwrapped" before the ratio indicated by Eq. 1 could be performed, since this is periodic data. A phase unwrapping algorithm was developed to achieve this result.

Fig. 1 shows the optical breadboard which has been in use for the current measurements. As can be seen, the signals from the three different interferometric path differences are all detected by a

single photo diode. The superposition of the three beat-frequency patterns as a function of time is shown in Fig 2 and raw data as collected in the measurement. The Fourier transform of this data yields frequency spectra centered around the primary beat frequencies associated with each path difference. The portion of the Fourier transform holding the data around the beat frequencies associated with the reference and measurement arms is shown in Fig 3. Hanning windows have been utilized to isolate the peaks and the spectra associated with the measurement and reference path differences are shown in Fig 3a and b respectively, and their inverse transforms are shown in Fig 4a and b respectively. (See eg. Burton et al.<sup>5</sup> for a discussion of Hanning and other windowing techniques) These periodic data are then phase unwrapped as shown in Fig 5a and the angular frequencies (Eq 2) retrieved as a function of time as shown in Fig 6. Note in Fig 6 the correlation in how each frequency changes in time due to the nonlinearities in the scanned laser diode output. When the ratio in these two frequencies is taken, the unknown length is given as a function of time through the sweep as shown in Fig 7, which is relatively flat, indicating the technique is ratioing out most non-linearities.

The mean value of the unknown length difference  $\langle X \rangle$  is then calculated from the N values of the ratios  $\omega_{sj}(t)/\omega_{Rj}(t)$ . For the data displayed above,  $L_{ref} = 49.600$  cm,  $\langle X \rangle = 71.164$ cm and  $\delta X = \sigma/\sqrt{N} = .00808$ .

At this point we have the following problem. The accuracy expected on the basis of the statistical analysis of the data is predicted to be better than the actual measurements of known changes in path difference. In the above case, the accuracy should be  $1:10^4$ , but a change in length of 1mm in the measurement arm is not detected while a change of length of 5mm is.

We have several ideas about why this is happening and will be pursuing the problem over the months to come. One problem is the

interference between the two frequency spectra as can be seen in Fig 3. When these two peaks are separated from one another using the Hanning window technique, overlapping portions in the wings of their spectra are thrown away. We plan to eliminate this problem by using a new optical layout with each interferometer having its own detector so that the spectra from each is independent. Next, we need to evaluate the effects of both amplitude and frequency noise in the laser source on the ultimate sensitivity of the system. Finally, we need to carefully review each step in our discrete Fourier transform treatment of the data to be sure important portions of the data are not being under weighted or inadvertently discarded. We also plan to change the windowing technique to employ super gaussian windows.

#### **All Solid State Ti-Sapphire Laser**

Construction of the frequency doubled, diode pumped Nd:Yag laser has begun. A design scheme similar to that described by Welford et al. is employed.<sup>6</sup> The 2.4 cm long "D" shaped cross sectional Nd:YAG rod is side pumped along its flat side by six 200 W diode arrays. Two three bar stacks of GaAlAs diodes emitting at 810 nm. are used. However, we are not temperature matching the wavelength to the center of the Nd:YAG pump band to reduce hardware. The rod has been placed in a short (20cm) cavity with a lithium niobate ( $\text{LiNbO}_3$ ) Q-switch and 60% reflective output coupler. The system is operated at 60% of pump capability so as not to require thermoelectric cooling at the 10 Hz rep rate. Cooling is conductive only, through the base mount of the laser.

Under these conditions, 9.4 mJ of energy is stored in the upper lasing level. The Nd:YAG laser has produced 1.8 mJ in a 18 ns pulse and 900  $\mu\text{J}$  in the frequency doubled pulse. Preparations are underway to frequency double the output and then to couple this to the 2cmx5mmx2mm Ti-Sapphire crystal using end pumping through a dichroic mirror.

### **References**

- 1) H. Kikuta, K Iwata and R Nagata, "Distance measurement by the wavelength shift of laser diode light", Applied Optics 25, 2976, (1991).
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- 3) Suematsu, M. and Takeda, M., "Wavelength-shift interferometry for distance measurements using the Fourier transform technique for fringe analysis", Appl. Optics 30, 4046, (1991).
- 4) Kay, R. B., Forth Semi Annual Report: NASA Grant NAG 5-1319, 1993.
- 5) Burton, D.R. and Lalor, M.J., "Managing some of the problems of Fourier Fringe Analysis", SPIE 1163, 149, (1989)
- 6) Welford, D., Rines, D.M. and Dinerman, B. J., 1991, "Efficient TEM<sub>00</sub>-mode operation of a laser-diode side-pumped Nd:YAG laser", Optics Letters

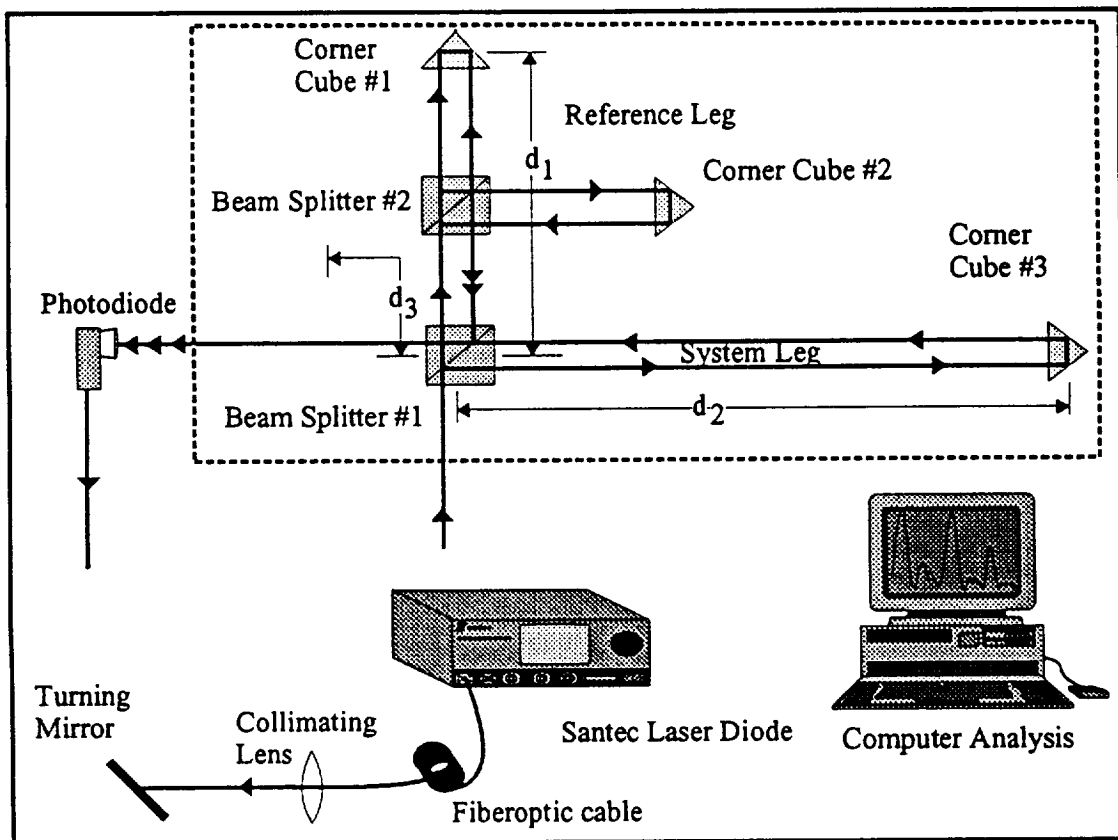


Figure 1: The three beam interferometer layout.

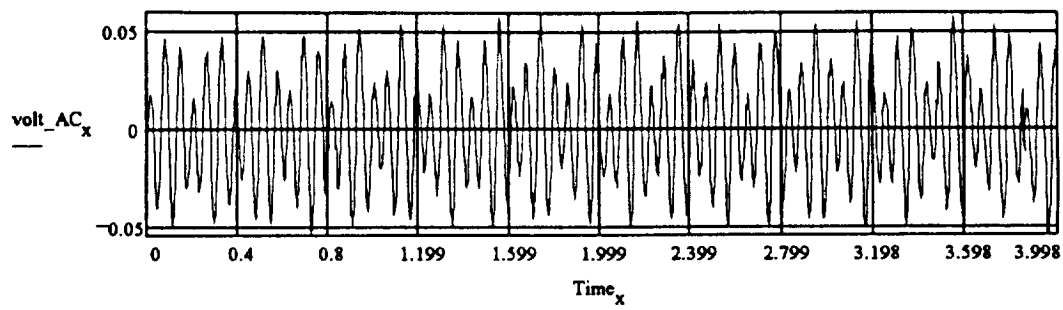


Figure 2: Signal on detector vs Time.

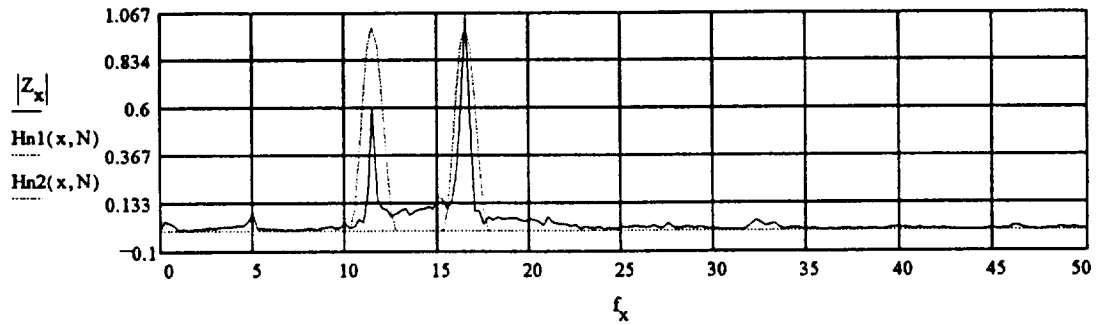


Figure 3: Portion of Fourier Transform in frequency space showing reference and unknown arm spectra, and Hanning window envelopes.

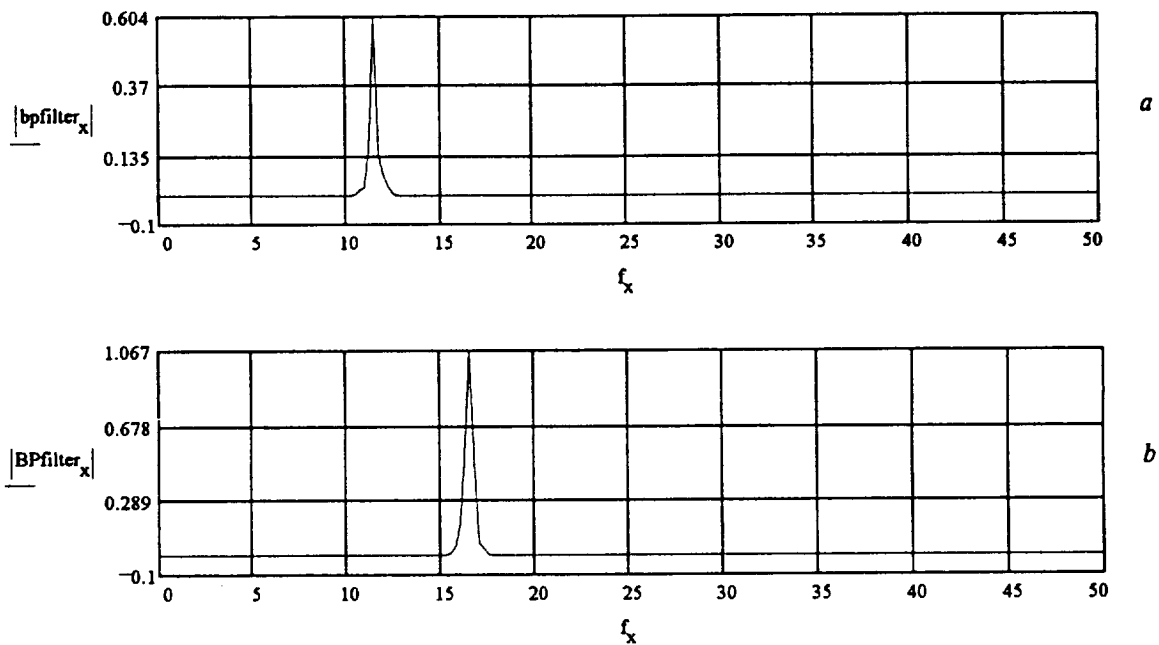


Figure 4: Windowed Fourier Transform peaks of (a) reference arm, and (b) unknown arm.



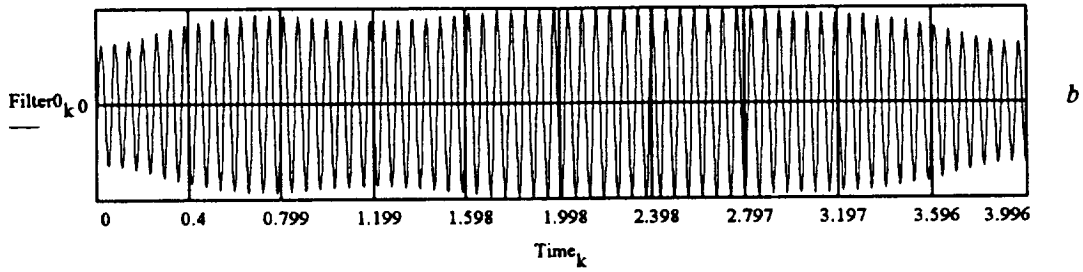
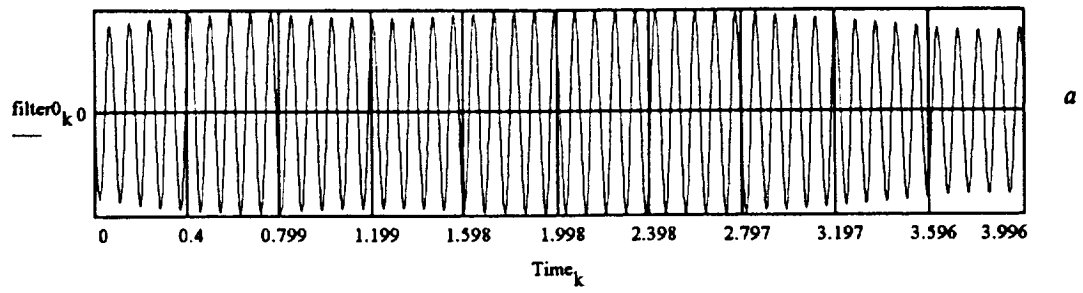


Figure 5: Inverse Fourier transform of the (a) reference arm, and (b) the unknown arm data.

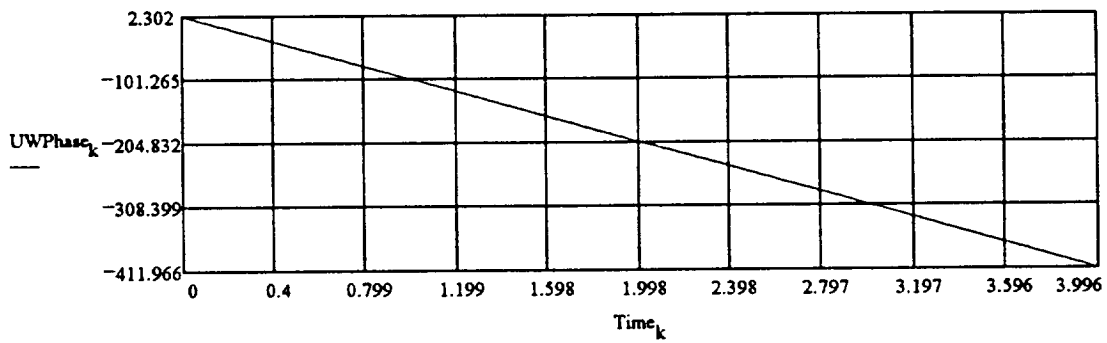
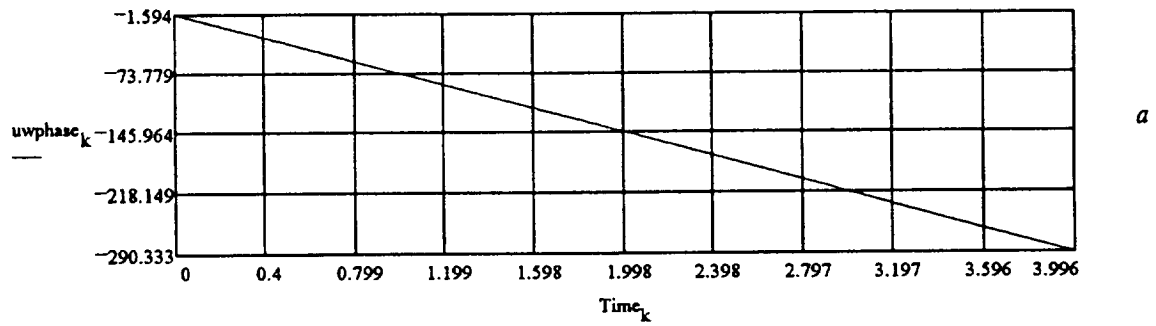


Figure 6: Unwrapped phase of the (a) reference arm, and the (b) measurement arm data of Figure 5.

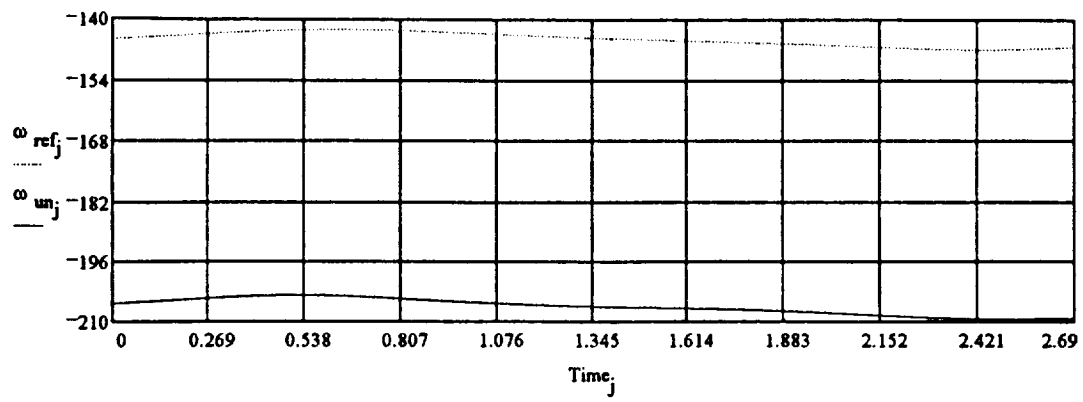


Figure 7: Angular frequency as a function of time from the reference and unknown arm data.

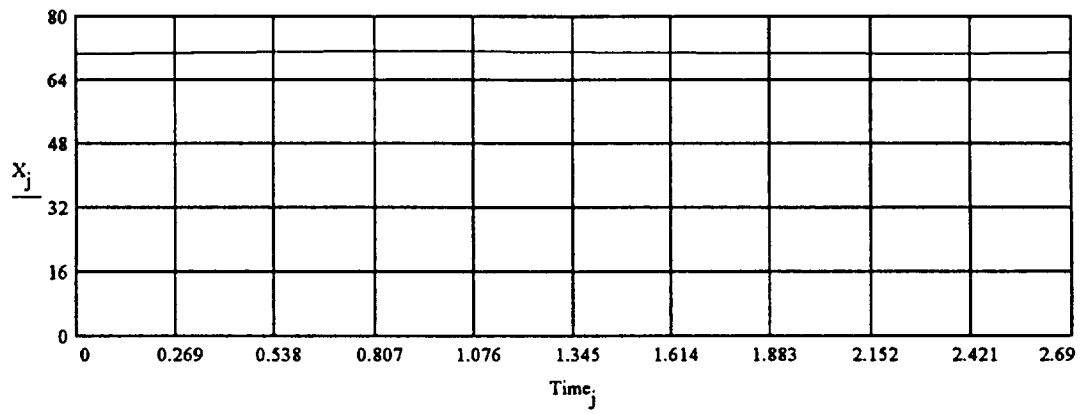


Figure 8: The unknown length as a function of time.